ENHANCED LATERAL OXIDATION

BACKGROUND

The invention pertains to laser light sources and particularly to vertical cavity surface emitting lasers. More particularly, the invention pertains to long wavelength lasers.

A vertical cavity surface emitting laser (VCSEL) may include a first distributed Bragg reflector (DBR), also referred to as a mirror stack, formed on top of a substrate by semiconductor manufacturing techniques, an active region formed on top of the first mirror stack, and a second mirror stack formed on top of the active region. The VCSEL may be driven by a current forced through the active region, typically achieved by providing a first contact on the reverse side of the substrate and a second contact on top of the second mirror stack. The first contact may instead be on top of the first mirror stack in a coplanar arrangement.

VCSEL mirror stacks are generally formed of multiple pairs of layers often referred to as mirror pairs. The pairs of layers are formed of a material system generally consisting of two materials having different indices of refraction and being easily lattice matched to the other portions of the VCSEL. For example, a GaAs based VCSEL may

commonly use an AlAs/GaAs or AlAs/AlGaAs material system where the refractive index of each layer of a pair may be changed by altering the aluminum content in the layers. In some devices, the number of mirror pairs per stack may range from 20 to 60 to achieve a high percentage of reflectivity, depending on the difference between the refractive indices of the layers. A larger number of pairs increases the percentage of reflected light.

In many VCSELS, conventional material systems may perform adequately. However, new products are being developed requiring VCSELs which emit light having long wavelengths. VCSELs emitting light having a long wavelength are of great interest in the optical telecommunications industry because of a low fiber dispersion at 1310 nanometers (nm) and a low fiber loss at 1550 nm. As an example, a long wavelength VCSEL may be obtained by using a VCSEL having an InGaAs/InGaAsP (or InAlGaAs) active region. When an InGaAs/InGaAsP active region is used, an InP/InGaAsP (or InAlGaAs/InAlAs or InAlGaAs/InP) material system should be used for the mirror stacks in order to achieve a lattice match to the InP substrate. The lattice matching between the substrate and the layers should be substantially close to ensure a true single crystal film or layer growth.

In the InP material based system, it is difficult to achieve a suitable monolithic DBR-based mirror structure having a reasonable thickness because of the insignificant difference in the refractive indices in this material system. As a result, many layers, or mirror pairs, are needed in order to achieve a useful reflectivity. Useful reflectivity may be 99.8 percent or greater. Numerous attempts have been made to address the problem of very thick mirror structures. One attempt included a wafer bonding technique in which a DBR mirror is grown on a separate substrate and bonded to the active region. This technique has had only limited success and also the interface defects density in the wafer fusion procedure may cause potential reliability problems. Other approaches to making satisfactory long wavelength VCSELs have been fraught with one problem or another. For instance, lattice matched InP based mirrors used for 1550 nm VCSELs may have a host of problems in growth, processing, and optical performance. The low index contrast of (or InAlGaAs) and InP (or InAlAs) tends to lead to a requirement of extremely thick (ten microns or thicker) DBRs of 45 or more mirror periods or layer pairs. The AlGaAsSb or AlGaPSb systems associated with an InP substrate may be difficult to grow by MOCVD; and for good contrast, may still require at least

25 mirror pairs to achieve adequate reflectivity for VCSEL operation. For some VCSEL structures, such as the long wavelength structures, current confinement is an important characteristic. Proton implantation and lateral oxidation have been developed and used for current confinement in vertical cavity surface emitting lasers (VCSELs) especially for GaAs-based VCSELs. For some VCSELs, however, proton implantation and lateral oxidation cannot be easily applicable due to either very thick top DBR stacks for proton implantation or lack of lattice-matched high aluminum containing material for oxidation. This appears to be the case of InP related materials for long wavelength VCSEL operation. For InP based material systems, since index contrasts are relatively small as compared to GaAs based counterparts, the DBR stacks tend to be much thicker to obtain reasonable reflectivity from the DBRs. Consequently, a huge amount of energy may be required for gain guide proton implantation of these stacks, which appears to be not practical. Such high energy may damage other parts of the VCSEL structure. Thus, lateral oxidation seems to be a necessary approach for a gain guide for current confinement and possibly optical confinement, and for device isolation. However, the aluminum content is significantly lower in materials lattice matched to InP

substrates than those materials lattice matched to GaAs substrates, which makes lateral oxidation difficult. Thus, a solution to the difficulty of lateral oxidation in InP based structures is needed. The invention provides a solution.

SUMMARY

The invention may involve a vertical cavity surface emitting laser having an InP substrate, a first mirror situated on the substrate, an active region situated on the first mirror, a gain guide formed on the active region and a second mirror situated on the gain guide. The gain guide may be an oxidized layer in the vicinity of the bottom portion of the second mirror proximate to the active region.

A gain guide layer may be initially grown or deposited as a layer containing some aluminum, and then oxidized. In the InP based system, the aluminum content of an acceptable material for a layer in the mirror may be about 52 percent. In the GaAs based system such acceptable material would have about 97 to 98 percent of aluminum content. The GaAs based layer may be relatively easy to oxidize. The oxidation of such layer may be done laterally along the side of the device via a trench around the top mirror plus

possibly the active region and bottom mirror, or vertical or other kinds of trenches inserted through a surface of the device. The oxidizable layer in the InP system may similarly be oxidized. However, because of the significantly lower aluminum content, that layer may be much more difficult to oxidize. The difficult process of lateral oxidation of the InP based oxidizable layer may be eased by intentional oxygen incorporation. The oxygen, a water vapor, or other fluid containing oxygen may be used an oxidizing or diffusing agent that is inserted into the oxidizing environment and/or layer containing aluminum to oxidize the latter. The term "fluid" may be a generic term which includes liquids and gases as species. For instance, water, air, and steam may be fluids.

BRIEF DESCRIPTION OF THE DRAWING

Figure 1 illustrates a vertical cavity surface emitting laser;

Figure 2 reveals an illustrative example of a long wavelength VCSEL;

Figure 3 reveals an illustrative example of a long wavelength VCSEL having a two part top mirror;

Figure 4 shows a structure of a VCSEL incorporating an enhanced oxidized layer approach;

Figure 5 shows the structure of Figure 4 with trenches;

Figure 6 shows a structure of a VCSEL with a two part top mirror, incorporating an enhanced oxidized layer approach;

Figure 7 shows the structure of Figure 6 with trenches;

Figure 8 shows a structure similar to that of Figure 4 having a coplanar configuration; and

Figure 9 shows a structure similar to that of Figure 6 having a coplanar configuration.

DESCRIPTION

Figure 1 is a representation showing a perspective illustration of a structure for a vertical cavity surface emitting laser 11. A substrate 12 may be disposed on an electrical contact 14. A first mirror stack 16 and a bottom graded index region 18 may be progressively disposed, in layers, on substrate 12. A quantum well active region 20 may be formed and a top graded index region 22 may be disposed over active region 20. A top mirror stack 24 may be formed over the active region and a conductivity layer 26 may form an electrical contact. Current may flow from upper contact 26 to lower contact 14.

This current may pass through active region 20. Upward arrows in Figure 1 illustrate the passage of light through an aperture 30 in upper contact 26. The downward arrows illustrate the passage of current downward from upper contact 26 through upper mirror stack 24 and the active region 20. An ion (proton) implantation 40 may form an annular region of electrically resistant material. A central opening 42 of electrically conductive material may remain undamaged during the ion (proton) implantation process. As a result, current passing from upper contact 26 to lower contact 14 may be forced to flow through conductive opening 42 and thereby be selectively directed to pass through a preselected portion of active region 20. The current may flow through bottom mirror stack 16 and substrate 12 to lower contact 14. The current going through active region 20 may result in a generation of light within a cavity constituted between top and bottom mirrors 16 and 24. Light may be eventually emitted by structure 11 out of aperture 30 as shown by the upward pointing arrows.

Figures 2 and 3 reveal several illustrative examples of long wavelength InP based VCSEL structures. A long wavelength may range from about 1200 nm through about 1800 nm. Figures 2 and 3 are not necessarily drawn to scale.

Structure 13 of Figure 2 may be a full epitaxial proton implantation version. It may have an InP substrate 15. On substrate may be formed a lower or bottom mirror 17. Mirror 17 may be a distributed Bragg reflector (DBR) having a stack of pairs 31 of layers 33 and 35 of materials. Each pair 31 may be one-half wavelength thick. Each of the layers 33 and 35 may be one-fourth wavelength thick. The thicknesses may be optical wavelengths of the light emitted from structure 13, for the respective materials of layers 33 and 35. The two layers, 33 and 35, of each pair 31 may be composed of different materials. For example, layer 33 may be InAlGaAs and layer 35 may be InAlAs. These layers and pairs may be repeated in a mirror stack. Other pairs of materials for layers 33 and 35 may include InGaAsP and InP, InAlGaAs and InP, GaAsSb and AlAsSb, and GaAsSb and InP, respectively. There may also be other material pairs that may be appropriate for making DBR mirror 17.

Situated on bottom mirror 17, may be formed an active region or cavity 19. Region 19 may have between one and more than five quantum wells. The material for the active region may be InGaAs (or InAlGaAs with low Al content) for quantum wells and InAlGaAs with high Al content for barriers. On active region 19 may be formed an upper or top mirror 23. DBR mirror 23 may have the same structure

of pairs 31 of layers 33 and 35 as that in bottom mirror 17.

Proton implantation may be applied at the lower part of mirror 23 to make a gain guide 21 to provide current guidance and confinement in VCSEL structure 13. A center portion on the top of mirror 23 may be masked with a material resistant to proton implantation. Then a proton implantation may be applied to the top of structure 13 resulting in an isolation 25. Since the indexes of refraction of each material of the pairs of layers are close to each other, then many more pairs 31 may be required to build the mirror with the needed 99.8 percent reflectivity. Consequently, top mirror is a quite thick epitaxial DBR. Thus, rather high energy is required to achieve proton implantation down far enough in mirror 23 to result in an effective isolation 25.

The mask may be removed from the central portion of top mirror 23. Another mask may be applied to the top mirror 23 with an opening for applying a contact metal 37 on the top of mirror 23. Structure 13 may be moved so the resultant contact metal 37 may be in the form of a ring. The mask may be removed after deposition for the contact metal 37. Another mask may be placed on a portion of the contact metal and a passivation layer 27 may be deposited

on the top of structure 13. The mask may be removed and another mask may be formed on the center portion of passivation layer 27. A layer of contact metal may be applied on the masked top of structure 13. The mask from the center portion of passivation layer may be removed with the remaining contact metal resulting in a ring-like contact 29 connected to contact metal 37. Contact metal may be deposited on the bottom side of substrate 15 to result in a second contact 39 for VCSEL structure 13.

Figure 3 shows a VCSEL structure 50 which may a regarded as a hybrid proton implantation version. As like structure 13 of figure 2, a mirror 17 may be formed on an InP substrate 15. The structure and materials used in the pairs 31 of layers 33 and 35 may be the same as those in structure 13. An active region on cavity 19, like that of structure 13, may be formed on mirror 17. On cavity 19, a first part 43 of mirror 47 may be formed on active layer or cavity 19. The material of pairs 31 of mirror part 43 may be the same as the pairs of bottom mirror 17 of this structure 50. Mirror part 43 may have fewer pairs 31 of layers 33 and 35 than bottom mirror 17 of this structure 50 or top mirror 23 of structure 13. One reason for the shorter mirror stack 43 may be to effect a proton implantation that results in an isolation 44 requiring much

less energy than the proton implantation required for making isolation 25 in structure 13. Proton implantation may be applied in a lower portion of mirror part 43 to make a gain guide 41 to provide current guidance and confinement in VCSEL structure 50.

On mirror part 43, another mirror part 45 may be formed. Mirror parts 43 and 45 constitute upper DBR mirror 47. Mirror part 45 is a dielectric mirror stack (DBR) that may be like a mesa or an island situated on lower mirror part or portion 43 of upper mirror 47. Mirror stack 45 may have, as examples, 3 to 4 pairs of TiO_2 and SiO_2, 2 to 3 pairs of Si and Al_2O_3, or 4 to 5 pairs of TiO_2 and Al_2O_3, respectively. The dielectric stack may cover the light aperture of VCSEL structure 50 and not block emitted light.

Formed around dielectric stack 45 may be a ring of contact metal as a first contact 46 for VCSEL structure 50. Contact 46 may be deposited in a manner similar to that of contact 37 for structure 13. A second contact metal may be deposited on the bottom of InP substrate 15 as a second contact 39 for VCSEL structure 50. A disadvantage of structure 50 is the process for making it is complicated by the making of stack 45 and related issues such as, for instance, stress in dielectric DBR stack 45.

Figure 4 shows VCSEL structure 60 which may be regarded as a full epitaxial oxide version. Lateral oxidation in upper mirror 23 may be resorted to for isolation and current confinement. On InP substrate 15, a lower DBR mirror 17 may be formed. Mirror 17 may have a stack of pairs 31 of layers 33 and 35 having material like that of mirror 17 in structure 13 of Figure 2. An active region or cavity 19 may be formed on bottom DBR mirror 17. Active region 19 may have one to more than five quantum wells. The material of active region 19 may include material similar to that of region 19 in structure 13. A top mirror 23 may be formed on active region or cavity 19. Mirror 23 may have a structure of pairs 31 of layers of material like that of mirror 23 in structure 13.

A thing about structure 60 that is different from structure 13 is that one or two of the layers of a pair 31, near active region 19 in mirror 23, may have a high content of aluminum. Such layers or layer having a high content of aluminum may be designated as layer 51. Layer 51 may instead be a layer or layers between top mirror 23 and active region 19. In other words, this layer 51 is oxidizable and may be oxidized laterally from the layer's external edge or via a vertical or isolation trench under certain environmental conditions having, for example,

oxygen or high water vapor and high temperature. Figure 5 shows an illustrative example of vertical trenches 52 for a structure 61, which is similar to structure 60. The result may be lateral oxidation 48 of layer 51 forming a gain guide 49 and providing isolation for VCSEL structures 60 and 61. Isolation 25 and a gain guide 21 as provided by proton implantation in structure 13 may be absent in structures 60 and 61.

Contact metal 37 and passivation layer 27 are formed on the top of upper DBR mirror 23 of structure 60 in the same manner as it is formed for structure 13. An electrical contact 29, connected to contact metal 37, may be made in the same manner as that for structure 13. Structure 61 of Figure 5 does not show electrical contact 29 or passivation layer 27. If those items were present, then trenches 52 may go through them. Contact material may be deposited on the bottom of InP substrate 15 to provide a second electrical contact for VCSEL structure 60. One apparent disadvantage relative to making the long wavelength structure 60 version may be a lack of speed in producing an appropriate lateral oxidation 48 to provide the desired gain guide 49, because of the low content of aluminum in oxidizable layer 51. The present invention circumvents that disadvantage.

By the way, the temperature for oxidation may be about 350 to 400 degrees C. in the case of lateral oxidation for a GaAs-based VCSEL. The oxidation temperature may be about 500 degrees C. for an InP-based VCSEL. The latter high temperature would not necessarily affect the other layers.

To make a layer easily oxidize laterally, the layer should contain a high aluminum concentration. A nearly lattice matched AlGaAs (Al=0.97 to 0.98) layer may normally be used for an oxidation layer for GaAs based VCSELs. In the case of InP based VCSELs, however, a nearly lattice-matched high aluminum containing layer is not available. However, a low aluminum containing material, InAlAs (Al=0.52), having a sufficient lattice matching characteristic, may be used in oxidation layer 51 on an InP based VCSEL. Under ordinary conditions, the latent lateral oxidation of InAlAs may take an extended time at a high oxidation temperature, which could cause other problems, such as quantum well mixing and diffusion of a mobile dopant. The InAlAs of oxidizable layer 51 may change to Al_xO_{1-x} when being oxidized.

The present enhanced oxidation may be effected in the following way. First, there may be diffusion of an oxidizing agent (e.g., water vapor or oxygen) into layer 51 via an oxide/semiconductor interface or edge, or trench.

Second, a chemical reaction (i.e., oxidation) may be initiated. A release of byproducts as a result of this oxidation or diffusion of the oxidizing agent may occur. But these byproducts may be absorbed, so generally there is little concern about them during the diffusion or oxidation. If diffusion of an oxidizing agent (i.e., O_2 or H_2O) is one of the rate controlling steps and oxidizing agents are already present in the layer, the lateral oxidation rate may be increased for a low Al-containing layer such as layer 51. Lateral oxidation rates may be small for InP system materials having aluminum.

Oxygen may be incorporated intentionally for enhanced lateral oxidation 48 of layer 51. Such oxygen incorporation may be carried out by with intentional oxygen doping of layer 51 with an oxygen-containing metalorganic dopant. Lowering the growth temperature of layer 51 may enable more oxygen to be put into that layer. This may make layer 51 oxidation a quicker process.

The proof of this enhanced oxidation process for low aluminum containing layer 51 may be shown by an oxidation sample that was grown after a metalorganic chemical vapor deposition (MOVCD) chamber was opened up for regular maintenance which permitted additional oxygen and water vapor to enter the chamber. It was previously known that

for a certain period of time, the chamber was expected to have a certain amount residual oxygen and water vapor. A sample like layer 51 was laterally oxidized in an oxidation process in the chamber. A much faster oxidation rate (7 to 10 micron lateral oxidation) than expected of the sample was observed. The faster rate turned out to be due to a greater amount of oxygen and water vapor in the chamber than the residual amount. The oxygen level of this sample was investigated with SIMS (Secondary Ion Mass Spectroscopy) and the sample was revealed to contain a high oxygen level (greater than the 10E19 order). The normal oxygen level of such sample oxidized under previous chamber conditions would have been in about the 10E16-17 order. Thus, the increasing the amount of oxygen in the oxidization environment or oxidation chamber of the sample or layer 51 may increase lateral oxidation rate of that sample or layer. Further, doping layer 51 with oxygen or vapor also may increase lateral oxidation rate of that layer. With either approach, one may cause an enhancement of the lateral oxidation rate by intentional oxygen incorporation even after all of the residual oxygen in the chamber environment of the layer is gone. The oxygen may be introduced in various fluids such as water vapor or in dopants of one kind or another.

Oxygen or water may be allowed to enter or purposely be placed into film or layer 51 during the growth of structure 60. Generally, one may avoid vapor entering into the other layers during that growth. A pre-existing amount of water vapor or oxygen in layer 51 may aid in the increase of the oxidation rate of layer 51 when oxidized.

Figure 6 shows a structure 70 that is similar to structure 50 of Figure 3. A thing about structure 70 that is different from structure 50 is that one or two of the layers of a pair 31, near active region 19 in mirror portion 43, may have a high content of aluminum. Such layers or layer having a high content of aluminum may be designated as layer 51. Layer 51 may instead be a layer or layers between mirror portion 43 and active region 19. In other words, this layer 51 is oxidizable and may be oxidized laterally from the layer's external edge or via a vertical or isolation trench under certain environmental conditions having, for example, oxygen or high water vapor and high temperature. Figure 7 shows an illustrative example of vertical trenches 52 for a structure 71, which is similar to structure 70. The result may be lateral oxidation 48 of layer 51 forming a gain guide 49 and providing isolation for VCSEL structure 70 or 71. Isolation 44 and a gain guide 41 as provided by proton

implantation in structure 50 of Figure 3 may be absent in structures 70 and 71.

Structures 60, 61, 70 and 71 may instead have coplanar configurations 80 and 90, shown in Figures 8 and 9, respectively, with or without trenches 52, having a second contact 59 in lieu of contact 39. Contact 59 may be situated on an intra cavity contact layer 58 which is situated on the top of lower mirror 17 and extending out beyond an edge of upper mirror 23 or 47, respectively. Structures 60, 61, 70, 71, 80 and 90 may have a configuration where top mirror 23 and 47, respectively, may be a mesa or island situated on the lower portion of the VCSEL structure.

Besides the use of the invention for InP based systems, there may be reasons for increasing the lateral oxidization of the oxidizable layer in the GaAs based material system such as the need to lower the oxidization temperature or to speed up the oxidation of the confinement and/or isolation layer, or to protect other elements of the system or device.

Although the invention has been described with respect to at least one illustrative embodiment, many variations and modifications will become apparent to those skilled in the art upon reading the present specification. It is

therefore the intention that the appended claims be interpreted as broadly as possible in view of the prior art to include all such variations and modifications.